

Analysis of Control Methods: Mercury and Cadmium Pollution

by Alan MacGregor*

Physical system conceptual models are developed to illustrate the various interconnecting pathways of metal flow. Economic use of mercury and cadmium, as representative toxic heavy metals, is inventoried, and the losses of each from the pathways of economic use are compared. Distinctions are made between high volume consumers and industries that are responsible for a large percent of total emissions or effluent loads.

The pathways of the metals in the environment are traced via the conceptual models. A global mass balance is presented for mercury. The problem of high local concentrations vs. global metal flow is reviewed.

Impacts of the metals on human health are categorized by type of effect.

Available control strategies and abatement measures are evaluated with respect to the effectiveness of each on the problems of metal pollution, as illustrated by the physical models.

Introduction

During the past few decades, our industrial society has made use of materials which are inherently dangerous to man. These "toxic substances" allow certain production processes to be operated more efficiently, and products containing these substances may be more effective in their desired use. Their characteristics of being permanent or persistent allow them to retain their toxic properties long after their economic or intended use has terminated. As many toxic substances are used specifically as economic poisons, society is indeed facing a great potential hazard.

Man relies greatly on natural dispersion processes to dispose of his wastes safely in the air and water environments. Quite often, the quantities of toxics that are released in one place are too great for safe levels of the pollutants to be maintained. Consequently, high concentrations can contaminate resources which may come in contact with man. Due to susceptibilities of the human body, even low doses of toxic substances may be disruptive to basic human metabolism.

This study concentrates specifically on heavy metals, as a subset of those toxic substances that are also naturally occurring. Hence, the problem can be one of both natural and economic factors. Within the list of metals which may pose hazards to human health, mercury and cadmium have been chosen as representative substances. These two metals pose air and water pollution and food contamination problems, and also problems of solid waste disposal. There are direct links of metal flow between the environmental phases of land, air, and water.

At the very heart of the matter is the fact that toxic materials, heavy metals in particular, and certainly mercury and cadmium, are harmful to human beings. A wide range of effects are known to be caused by exposure to varying amounts of these metals. Low doses over long periods of time can produce disorders with confusing symptoms due to uncertain routes of exposure.

At this time, it does not appear that a way exists to immunize our bodies against exposure to heavy metals, as we have for polio or smallpox. It appears then, that to gain knowledge of the routes of exposure is the appropriate course of study. This study centers on the pathways by which the metals are taken from their natural locations for economic and noneconomic uses, emitted and transported

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through the environment, and eventually cause problems of resource and product contamination. By defining the problem with heavy metals to be one of resource and product contamination (with the assumption that these resources and products are to come in contact with man), a systematic investigation of the pathways of metal transport will establish an understanding of how the "problems" are brought about. A knowledge of all paths of exposure is essential to the effectiveness of a control strategy.

The Problem with Heavy Metals: A Conceptual Model

First, a conceptual model will be developed which will segment the inclusive topic of heavy metal flow into a number of smaller sub-models. On the general mode (Fig. 1) certain "black boxes"

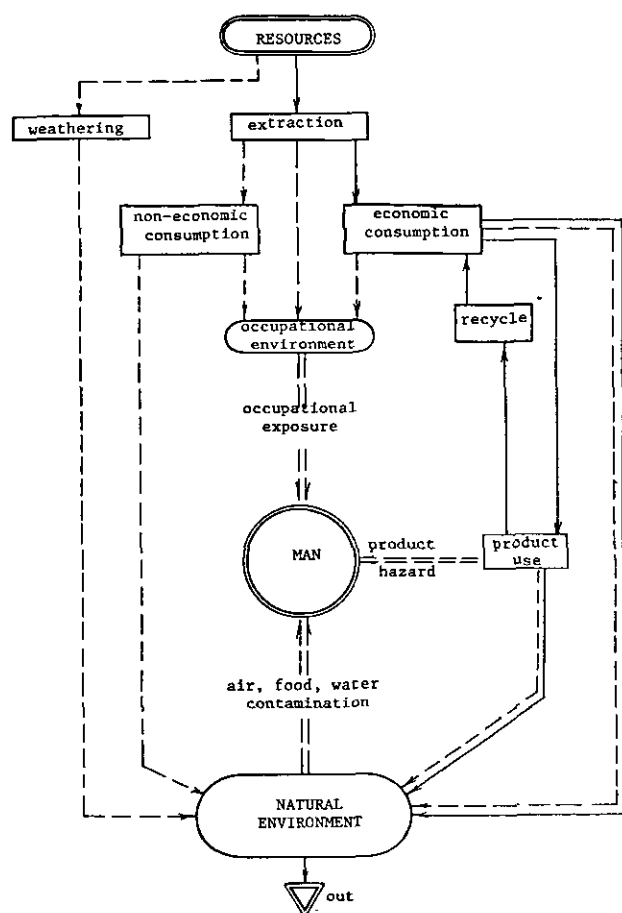


FIGURE 1. Schematic metal flow.

are established which symbolize complex systems of interconnecting metal paths. The purpose of the first model is to set out the pathways in logical groupings. The paths as pictures will show the various black boxes relate to one another, and how the boxes and paths relate to the problem of resource contamination.

Economic use refers to the consumption of metal-bearing resources (ores) where the metal itself is the material of direct interest. Noneconomic use refers to resources which contain mercury or cadmium but are extracted and used for purposes where these two metals are not important to the desired product or process. As mercury appears in fossil fuels, emissions of mercury that result from combustion of coal and oil are termed "non-economic." Similarly, cadmium appears in fertilizers, although it is not an additive or a desired component.

By definition, the metals are not recovered or recycled via noneconomic use and therefore are "lost" to the environment. The naturally occurring pathways that are the result of the geologic processes of weathering, usually most closely associated with the erosion of the earth's crust.

The dashed lines on the figure indicate that the pathways are not intentionally created by man. The pathways of weathering and of the environment are naturally occurring; the ones associated with noneconomic uses are not intentional but rather are a function of the economic use of an independent resource. The solid lines indicate paths of man-controlled, intentional metal flow.

Losses to the environment from the economic system during production are both intentional (if production wastes are not recycled) and unintentionally (if accidental losses or faulty pollution control devices exist).

Associated most closely with economic consumption and extraction, but also to a small extent with noneconomic use, is the "black box" of the occupational environment. In several industries, the contamination of the workplace is a serious problem in and of itself or together with environmental contamination. Through occupational exposure, the worker may come in contact with metal concentrations which are orders of magnitude higher than in the natural environment. This may be harmful in its own, or together with other sources of exposure such as eating certain foods.

As the manufactured products are used, the pathways associated with metal use, recycle, and disposal are initiated. Certain products are characteristically of a recyclable nature. Others, due to economic or technical reasons, are disposed of

when their use is terminated. The solid line from "product use" to "natural environment" symbolizes these disposal pathways as well as products which are of a dissipative nature and are discharged directly into the environment. The dashed line from "product use" to "man" could imply that only through accidental or unforeseen or unintentional circumstances will man be exposed to metal-contaminated products. Actually, this is not the case. Several common household items contain mercury and cadmium. Under normal or use in accordance with instructions, no exposure will occur. The danger exists, nonetheless, and hazardous exposure could be the result of a number of accidental or unforeseen events.

From the standpoint of human health, three pathways are seen to have potential adverse effects; occupational exposure, unintentional exposure due to the use of products, and exposure due to resource contamination. Earlier it was suggested that the third path was the most central to the problem of human exposure to heavy metals. The human receptor is usually unaware of contamination of his food or water, and has little choice concerning the quality of his air. In general he is ignorant of the dangers of possible exposure. Occupational exposure is less central to the human health problem as only selected portions of the population are in danger and awareness of hazards can be expected to arise relatively quickly. Although metal concentrations in the air may be high, the routes of

exposure are certain and the problem of where to apply controls is not difficult. On the other hand, the problems of which environmental resources to control, or even monitor, are more uncertain.

The hazard associated with the use of metal-contaminated products produce resource contamination problems that are generally similar to those resulting from environmental contamination. Hence, the concentration on the critical paths of resource contamination will necessarily include a study of certain product hazards.

Economic Uses

When an ore of mercury or zinc and cadmium is extracted for economic purposes, a series of transport and transformation pathways are initiated. These paths can be considered economic in nature until the final metal product use is terminated and is no longer of any value to man. Not all of the metal content of the ores makes its way to the product stage; in the various physical and chemical processes involved in manufacturing the product, some metal is lost from the economic system. These losses can be captured and recycled if both a technology and an incentive exist; they can also be discharged into the ambient environment as specific air emissions, fluvial effluents, or solid wastes.

The distribution of the consumed mercury metal among the industries by quantity and by percentage of total metal consumed is shown in Table 1.

Table 1. U.S. consumption of mercury in 1971.^a

Type of product use	Industry	Mercury consumption	
		Tons	% of total consumption
Long-term	Electrical apparatus	643.6	32.3
	Measurement and control devices	185.1	9.3
	Laboratories	68.7	3.4
	Subtotal(1)	897.4	45.0
Dissipative	Paint additives	327.0	16.4
	Dental amalgam	90.7	4.5
	Agricultural	56.1	2.8
	Pharmaceuticals	25.9	1.3
	Subtotal(2)	499.7	25.0
Production of nonmetal product	Catalysts in chemical manufacture	43.4	2.2
	Chlorine-caustic soda	466.0	23.4
	Pulp and paper	0	0
	Subtotal(3)	509.4	25.6
Miscellaneous known uses		87.4	4.4
Unknown Uses		0.2	—
	Grand Total	1994.1	100

^aAdapted from U.S. Geological Survey data (1).

The industries are grouped into three general categories by the type of product. Long-term uses (which have potential for recycling), dissipative uses (which have no such potential), and production of a nonmetal output (in which no mercury should appear in the final product). For the chlorine-caustic soda industry, the mercury is used in large electrolytic cells. As no new mercury cells have been built since 1970 (Chlorine Institute, New York, private communication January 1974), the quantity consumed does not include any metal used in start-up operations.

Cadmium is always found in some ratio (in ore) to zinc, copper, and lead, zinc being the most attractive economically. Cadmium will also appear in some ratio to zinc as an impurity in any use of zinc. The cadmium impurity will be larger if at the time of ore purification the particular plant had no interest in the recovery of the cadmium. Several purification works treat both zinc and cadmium, while others process only cadmium.

Based on estimates of cadmium content of extracted ores and imported flue dusts, and estimates of atmospheric emissions, 478 tons of cadmium were lost to the environment as impurities in zinc metal and in tailings from ore processing. The atmospheric emissions are a result of stack emissions from ore smelters. If cadmium is the desired metal, it is recovered by heating the ore until the cadmium is volatile; the cadmium fume is recycled and the dust, either cadmium oxide or cadmium sulfide, is recovered. Stack gases are passed through bag houses or electrostatic precipitators to collect the dust. Some plants process both zinc and cadmium, others the flue dust from zinc, copper, and lead smelters. The cadmium fume may have to be recycled several times before the content is high enough to collect the dust; most emissions occur at this stage in purification. Cadmium is not used in the manufacturing process of a nonmetal product, and is used in only one dissipative use (fungicides). The industries are placed into categories based on product types; metal and nonmetal. In the latter, cadmium appears as an intentional ingredient. Table 2 shows the consumption of each industry for the study year 1968.

Consumption in 1973 was less (2), with nearly the same percentages per industry. The exception is the battery industry, which now accounts for 15% of cadmium consumed. This use is expected to continue to increase (J. M. Hague, U.S. Bureau of Mines, personal communication, June 1974).

Although not intentionally, man is responsible for the release of metals into the environment through non-economic activity. The metals are

Table 2. U.S. consumption of cadmium in 1968^a

Products	Cadmium consumption	
	Tons	% of total
Metal products		
Electroplate	3,000	45.0
Alloys	500	7.5
Batteries	200	3.0
Subtotal (1)	3,700	55.5
Nonmetal products		
Pigments	1,400	21.0
Plastics	1,000	15.0
Fungicides	12	.2
Miscellaneous	552	8.3
Subtotal (2)	2,964	44.5
Grand total	6,664	100.0

^aFrom U.S. Geological Survey data (1).

released through the extraction and use of other resources. The metals themselves do not appear in high enough concentrations to be of economic value or of importance to the product. These non-economic sources do contribute to environmental metal flow, and are therefore important to this study.

Figures 2 and 3 illustrate the links between industrial activity, natural (noneconomic) sources, and the environment. The metals follow pathways of losses and wastes from certain manufacturing operations to air, water, or solid waste receptors. Certain product pathways are shown to illustrate the interrelationships of certain industrial pollution sources. In addition, all of the industries pictured are directly related to extraction and refining operations.

By inspection of the quantities of metal estimated to be lost in certain pathways, the relative impact of a category of industries on a particular phase of the environment can be determined. A comprehensive study of mercury and cadmium losses to the water and soils would complete the model and allow a judgment to be made concerning the offensiveness of the industry on the environment as a whole.

Mercury in the Natural Environment

Recent studies have confirmed the possibility that inorganic mercury in the aquatic environment is converted to organic methylmercury by microorganisms. The implications of the methylation process are severe. Inorganic wastes are as dangerous as organic mercurials through a naturally (and readily) occurring process (5).

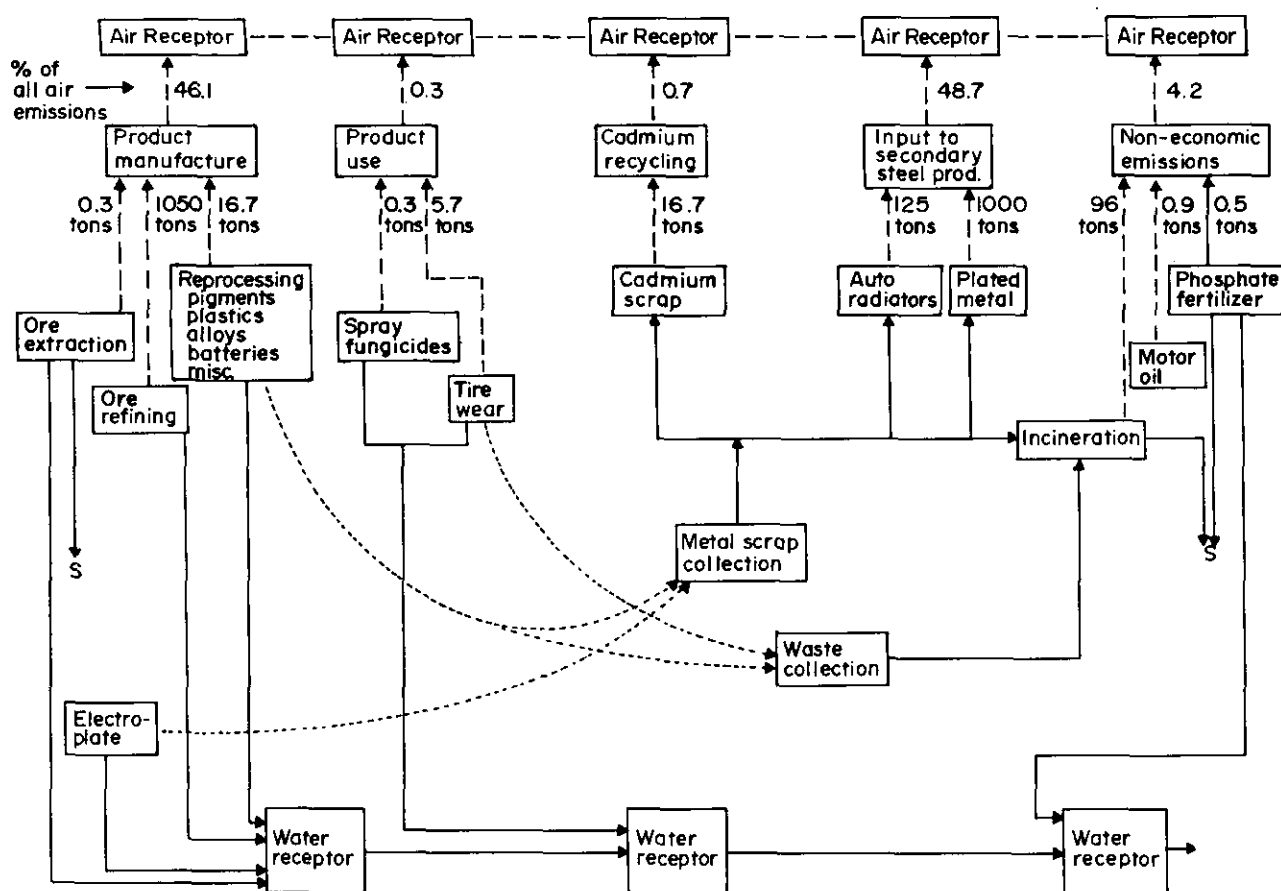


FIGURE 3. Cadmium environmental receptors. Percentages and emissions estimates derived from Davis (3).

the turnover rate. The two week value seems acceptable, if rainfall is that frequent. It is known that mercury is confined to altitudes of only a few hundred feet (7). Consequently, a high outgassing rate may or may not sustain a high burden, if a short residence time actually exists.

As for weathering processes that affect the aquatic systems, Anderson matches Joensuu's estimate for the air receptor and sets a rate of 250 tons per year. Anderson supports this total weathering rate of 500 tons by estimating that 500 tons are also removed from the system yearly by settling into the deep ocean sediments. Gavis and Furgeson (8) calculate that 800 tons are mobilized naturally each year. Bertine and Goldberg (9) suspect a higher rate, 5000 tons, but calculate that 2000 tons are lost to the sediments of the rivers and estuaries and that only 3000 tons reach the ocean.

Although earlier estimates were orders of magnitude less, the oceanic mercury content is now judged (11) to be approximately 10^8 tons.

Man's impact on the mercury system will be considered now. World production is about 9000 metric tons (12). In addition, nearly 1000 tons are probably lost in extraction and refining. From estimates (4) of the amounts of wastes that enter each environmental receptor, 2300 tons are added to the air system, 24000 to the water, supported by Weiss et al. (14), and 300 to the soil, all as a result of man's economic uses. In addition, fossil fuels, due to mercury content, add some 5000 tons total (11). Gavis and Furgeson (8) estimate 3000 tons from coal combustion and about 1800 from oil refining and combustion.

From these estimates, the global mass balance of mercury summarized in Figure 4 was constructed. For the atmosphere, as more than one estimate or quantity exists, the higher emission rate is associated with the higher atmospheric burden. The problem with mercury flow is seen as being the failure of the natural system to remove the metal at the rate it is being added by man. In particular, the

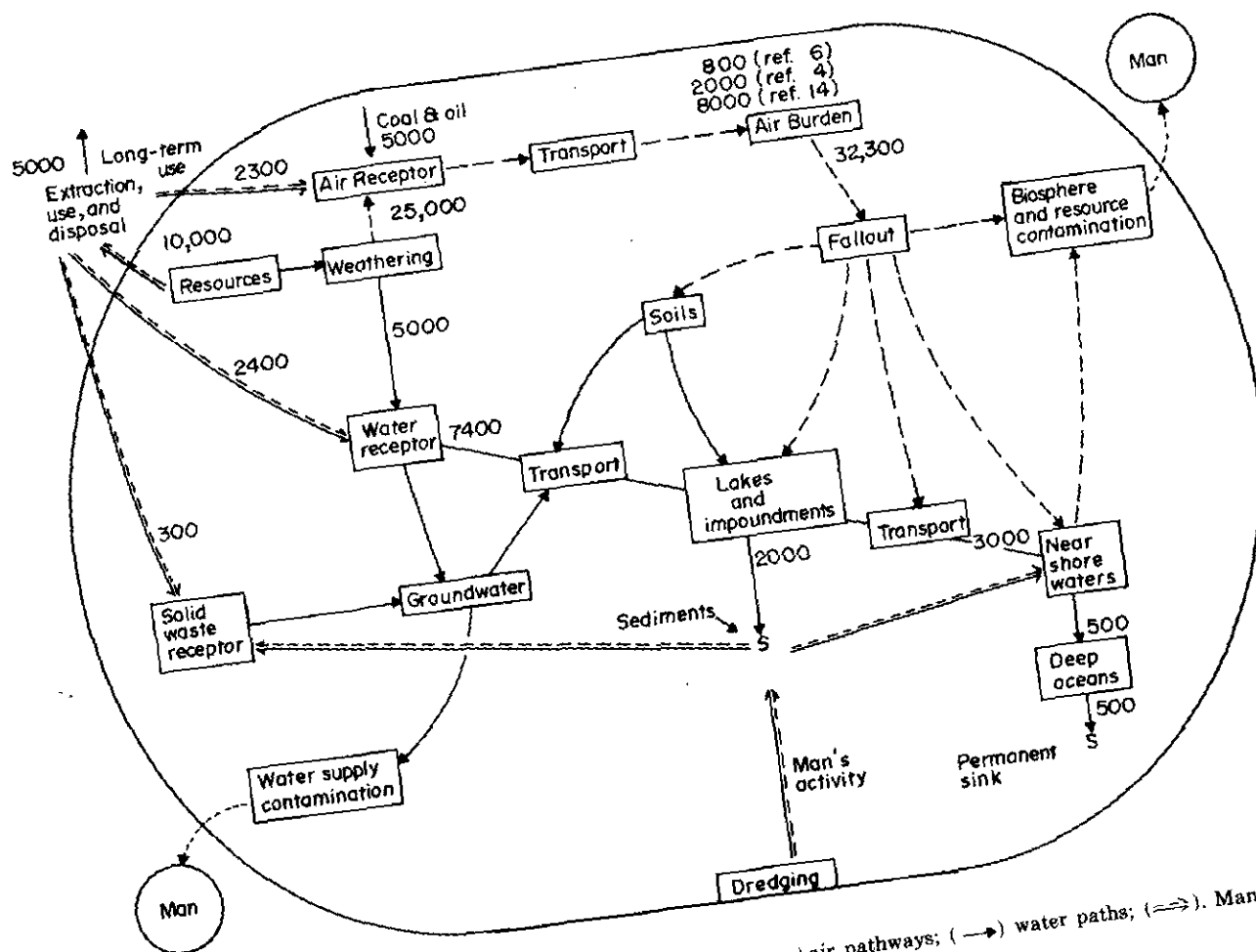


FIGURE 4. Environmental metal flow, global mercury balance: (---) air pathways; (—) water paths; (····). Man-induced transport; (····) human exposures; (s) sediment sink. All data in tons/yr.

metals will collect in sediments and estuaries, as the mechanisms that move them downstream and into the ocean depths can not accommodate the high loadings imposed by man.

Model Summary: Systems of Metal Transport

The models that have been presented form a description of the framework of the heavy metal pollution problem. From the standpoint of relative criticality, collected estimates of emissions, effluents, and general metal flow tend to make the models more powerful. However, it is not a most efficient solution to investigate all of the ecological and biological transport rates to develop an in-

clusive working model of the metal-control system. Even if the effects of existing and new control systems could be predicted, the time, money, and various assumptions necessary to build a workable model would detract from its utility. A somewhat arbitrary system of monitoring of levels in various modes and collection of such data may be a more economical and feasible solution to check the need or results of any control measures.

The central problem with heavy metals is that they often collect in concentration that cause resource contamination. The second half of the problem, inseparable from the first, is that these resources are used in some way by man. "Contamination" can be taken to mean levels that will be hazardous to human health if they come in contact with the body. Air, public water supplies, and

food products are the resources that are chiefly affected. These are resources that when consumed are generally taken to be nontoxic. With air and water, the human has essentially few options to improve the quality of his resources.

As a summary to the models presented in this paper, the following conclusions will be offered to highlight the critical mechanisms, that through displacement, contribute to the problem of resource contamination.

The metals are "nondegradeable" in that they are disassembled into less harmful components. The metals thus turn the short-term problems of product use into the long-range difficulties of accumulation, persistence, and chronic human disorders.

The metal system of zinc is very important to a study of cadmium as the metals are found together in nature. Cadmium appears as an impurity in most zinc products. Biologically, the unnecessary cadmium may interfere with the desired activity of zinc if the zinc-to-cadmium ratio is disturbed.

The wasteful residual byproducts of industrial activity, if carefully removed from air, water, gas, and products by sophisticated antipollution equipment, still must be managed carefully (often as solid wastes) to minimize the chances of their unintended recurrence.

Metal recycling may not have a great effect on the contaminated resource problem. Although 70% of mercury products are of a nondissipative type, at most only a third of production is recovered. Only 4% of new cadmium metal came from scrap collection in 1968 (1). No effort is made to recover the cadmium from steel during scrap collection for the steel industry, and recovery from plastics is not likely to be economical.

Mercury poses some difficulties, as natural contributions are significant in stream and ocean concentrations. Cadmium seems to pose no problem in this area and also does not appear in an organic form.

Biomethylation is significant in that most forms of inorganic mercury can be transformed into a more dangerous form. Regulating only organic wastes is therefore not a good policy, as evidence shows that the rate of conversion of inorganic wastes in fresh water sediments is fast enough to cause food chain contamination.

The global flow diagram permits the routes of metal flow that produced a specific resource problem to be "traced back" to discover the paths that could contribute to the problem. It is seen that the burning of fossil fuels contributes twice as much mercury to the atmosphere as do emissions from industrial uses of mercury.

The pathways for cadmium exposure to the human organism were from residues on crops, from shellfish and other aquatic organisms that accumulate the metal, from a contaminated water supply, or from erosion of the zinc (and hence cadmium) lining of galvanized pipes in the water distribution network.

The group of pathways that are most accessible to controls are those of economic wastes. Losses to air and water receptors and solid wastes disposal are significant in comparison to natural sources. Due to the methylation process, mercury losses to the aquatic environment should be strictly controlled. In this case the safe assimilative capacity of the water body is extremely low. Economically, these pathways are most attractive to control as they will serve as a source of secondary metal as the wastes are recycled.

Airborne wastes have a less direct effect on human health as adequate dispersion from economic sources and noneconomic sources (i.e. power plants) exists. However, the metal that is mobilized will settle out of the atmosphere where it can contaminate water resources. High background levels in certain areas may be due to atmospheric transport of mercury and cadmium over great distances.

Human health is most directly protected by monitoring of man's consumable resources. Ambient air testing and testing of foods that often have elevated metal levels are procedures that should be continued. At some future time when these tests consistently reveal insignificant concentrations, they can be discontinued.

Effects of Exposure to Mercury and Cadmium on Human Beings

Walker (16) makes the statement that "...the possibility exists that many unusual deaths which periodically occur in our society may have been caused by toxic chemical poisoning, but were never diagnosed as such because the doctor or coroner failed to recognize symptoms of such poisoning."

Several explanations are possible: (1) the doctor or coroner was unaware of the specific symptoms of toxic substance poisoning or could not discern among their subtleties; (2) a multiple cause of death existed where the less obvious condition of intoxication was masked by some other ailment; (3) a complex synergism of more than one substance produced death. For example, workers exposed to air-borne asbestos fibers who are also

heavy cigarette smokers breathe two separate groups of particulates that when combined are significantly more hazardous to human health than either substance independently (17). The absence of a certain body nutrient in combination with the presence of a toxic substance is another possibility that may hinder accurate diagnosis of an ailment.

The dietary practices of a nation are representative of various societal patterns that allow certain groups of humans to be especially susceptible to poisonings by heavy metals. The danger of mercury poisoning in the United States, due to the ingestion of contaminated fish, is much less than the danger in Japan, a nation whose people have a much greater dependence on fish as food supply. Since tuna and swordfish have always shown elevated levels of mercury (5), Americans are fortunate that such foods did not comprise significant portions of their diet. The Swedish and American standards of 0.5 ppm are diet-dependent, as they were calculated on the basis of average weekly fish intake (19).

The medical explanations of why such poisonings and effects occurred are often complete explanations descriptions of the causatory mechanisms; the tragic nature of such explanations is that they are offered after such poisonings occur. The prediction of what will happen under various conditions can only be based on our past examples of human health effects. The complexities of human body responses to various combinations of "elevated" concentrations and "deficiencies" are too great to consider as a foolproof way of heading off toxic epidemics. The best that society can do is to apply the knowledge of past poisonings to the possible routes of exposure to heavy metal pollution.

Two quantitative indicators are often used in the setting of safe standards of exposure to heavy metals. The acceptable daily intake (A.D.I.) is used to calculate safe levels of the metals in foodstuffs. The A.D.I. is a function of the dose that is known to cause symptoms of poisoning and the amount of the particular food in the average diet. A safety factor is included to protect the most susceptible segments of the population. The second quantitative indicator is the total body burden. This value is the calculated mass of metal in the body at a certain time. Although this concept is most closely related to the effects on the body of the metals, the relationships between intake, absorption, and distribution among the organs of the body are under investigation and the use of the A.D.I. is more popular in standard setting. If the effects of certain doses of the metal are known, the A.D.I. becomes the best way to impose dietary restrictions.

If the A.D.I. concept is to be used, the agency setting the standards must be aware of alternate paths of exposure so that the total body burden does not reach dangerous levels even though the legal A.D.I. for food has not been exceeded.

Control Strategies and Environmental Pollution Control

The best overall control system will be a mixture of several strategies. Each may be pursued to a different extent for different industries and population groups. The management decisions concern the degree to which each strategy will be pursued and the methods to use in each situation. Categories of strategies are described below.

Source Controls

There are two technical categories of source control mechanisms. The first, product control, involves certain restrictions that prohibit the metal to appear in certain outputs. This could involve certain alternative ingredients, such as nonmercurial fungicides in paints. It would also involve the purity of a product. If serious enough, a ban on the product may be necessary and alternatives to the product as a whole need to be found. The use of mercury as an amalgam (recently terminated) is such an example. Under the Federal Insecticide, Fungicide and Rodenticide Act and the Federal Food and Drug Act, the government has authority to regulate products that contain poisons or in fact are dangerous to man.

The second technological control concerns residual management. By making the process cleaner via either process modification or more efficient pollution control apparatus, the industry will reduce "losses" to the immediate environmental receptors. The collected metal could be recycled internally or sold to a reprocessing plant. The Federal Clean Air Act and the Water Pollution Control Act (as amended) are the primary legal controls; the Refuse Act permit system, the Solid Waste Disposal Act, and the Resource Recovery Act may also be applied to heavy metals. Enforcement involves the setting of standards, a system of monitoring (and hence data additions to a mass balance) and either a tax-incentive program or legal action against violators. The liability of certain plants or industries to the public and to the environment is a matter which will have a major effect on the social economies of pollution. This is particularly true for heavy metals, as the problem of laden sediments hampers future use of various water associated resources.

It should be noted that both of the technological control strategies have the effect of reducing the amount of new, virgin metal entering the system. An overall decrease in the consumption rate will not solve all of the existing difficulties, but is certainly a necessary condition of a system of controls.

Pathway Control

Pathway control is difficult in the case of heavy metals. As naturally occurring elements, they have certain transport phenomena that are impossible to modify. The Department of Transportation Act and the Hazardous Cargo Act are a means of regulating overland transport from the safety-accident standpoint. The regulations involving interstate commerce are the means of enforcing certain federal product bans. The location and practices of certain landfills must be regulated to protect aquifer water supplies from contamination. Finally, methods are being considered to remove mercury sediments from stream beds, as they are involved in the bioproduction of methylmercury (20).

Safe Product Use

Safe product use involves a system of clearly printed restrictions on the use and disposal of metal products. Such products safe enough to be produced but may have a hazardous effect on man and his environment via accidental exposure.

Occupational Hazard Control

Occupational safety is of concern because workers are allowed to endure average levels for an 8-hr day that are much higher than ambient levels that would cause concern. In addition, peak levels of inhalation are not specified and can be responsible for certain acute poisonings. There is concern that the occupational standard for cadmium inhalation, if maintained in a work environment, could produce chronic poisoning within 2 yr (21), whereas a non-occupational exposure would not produce chronic effects for 50 yr at even the most adverse combination of dosages.

Human Health Protection

A system of resource monitoring is necessary to protect the consumer from many products that reach the human receptor which do not have heavy metals as intentional product ingredients. Water and food supplies must be checked periodically to

detect natural and unintentional concentrations of the metals.

Certain control mechanisms that may work for other substances are not applicable to heavy metals for the reasons evident from a study of the presented models. Gutmanis (23) finds the mechanisms of dispersion, dilution, detention, diversion, environmental treatment, and desensitization as not being useful in control of pollution by mercury. Cadmium may follow much the same guidelines. A tax-incentive system may not be desirable as the accumulation and permanence of the effluent metals could not reasonably be included in the application of such taxes.

The questions of what to try to control, what to leave alone, and what to investigate further are difficult to answer in that complex economic social costs and certain political realities may be considered. The control of hazardous substances in our environment should go far beyond the obstacles of economic impacts and political feasibilities if public health and environmental quality are to be protected.

Role of Physical System Models in Pollution Control and Environmental Management

The use of the physical models has helped to identify several of the critical characteristics of heavy metal pollution. It was seen that a large industrial consumer of a toxic metal may not immediately be a major source of environmental pollution. On the other hand, a relatively small industry may be directly responsible for environmental metal flow if the product is of a dissipative nature.

The extent that metal recycling is used was illustrated. The limitations placed on future recycling efforts were seen to be limited by the characteristics of the products rather than by the economic costs of metal recovery. Some products that either incorporate mercury or cadmium as an ingredient or use the metals in a manufacturing process can be equally useful if substitute materials are employed. The biocide properties of mercury are equaled by less persistent chemicals which are also economically attractive.

The reduction of total metal flow is seen as a way of reducing the criticality of all the pathways. Certain particularly offensive pathways should be severed immediately, but an increase in virgin metal flow can only mean more metal eventually circulating in the environment. The bioconversion processes of methylation make the attention given

only to organic mercurial wastes seem futile. All aquatic mercury wastes or wastes (seen on the flow charts) that can enter the aquatic system are potentially critical. The conversion to the far more dangerous organic form was seen to be possible under a range of water quality conditions.

Although the models in this paper are not predictive, the long-term hazards of exposure to mercury and cadmium are certainly clear. Products with long-term uses are still eventually disposed, metals in sediments have an extremely long residence time, and chronic exposure over many years is an ever-present danger with both metals.

The defined problem of resource contamination was shown to be closely related to other typical environmental problems. Materials were collected for economic purposes and then discarded into a convenient environmental receptor. The problem of "displacement" from a materials flow standpoint is a result of wasteful practices, ignorance on the part of industry and incomplete conduct of regulatory responsibilities. Related to this concept are the problems of the social cost of disposing these hazardous wastes in the environment. For heavy metals these costs have not been noted, let alone internalized.

Certain critical points in the paths of metal flow have appeared on the models. At first glance it may seem that the dispersion processes of the atmosphere are more effective on heavy metals than the processes of the aquatic system. Although this is the case, the environmental flow model has illustrated that there are connecting pathways between the various parts of the environment. Mercury and cadmium air emissions are not, therefore, entirely harmless.

The control strategies that can be applied to the problem of heavy metals are indeed varied, but all must meet a first criterion of reducing total metal flow. Due to the bioconversion processes associated with mercury, aquatic disposal of all mercuric wastes should be stopped. Whenever possible, substitute ingredients should replace mercury and cadmium. In most cases the cost of production is not adversely affected.

Further application of controls will be a mixture of a number of strategies. Product substitution, metal recycling, and metal resource recovery (from long-term products) all have associated costs of program implementation which must be balanced against the effectiveness of the controls. The resultant control strategy that is most efficient will take careful account of both the transaction and implementation costs as well as the social costs, which the people will indeed bear.

The setting of a standard for dietetic or food residue levels of metals must be undertaken with a knowledge of acceptable atmospheric concentrations and metals in the water supplies. The standards must be coordinated with a knowledge of how the total amount of absorbed metal (the total body burden) will effect the organism. It is important to be aware of the existence and criticality of all paths of exposure in the setting of a standard for any one path.

The problem of heavy metal toxicity is one that if uncontrolled will affect a significant portion of our population over a period of decades. In light of the progress made in the last 5 yr (since the "mercury scare") it is probable that catastrophes like Minamata and the Itai-Itai cases will not be repeated. Chronic exposure is still a danger as a great deal of these metals are still being used in our economic system. Accidents which produced the Huckleby and Iraqi poisonings could still very easily happen. Finally, it can be said with assurance that all of the hazards of these metals are not yet known.

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